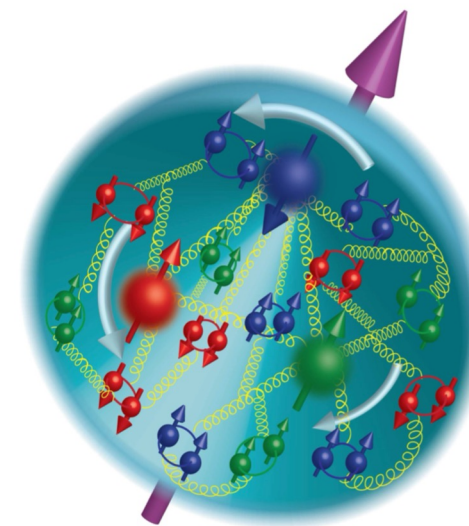
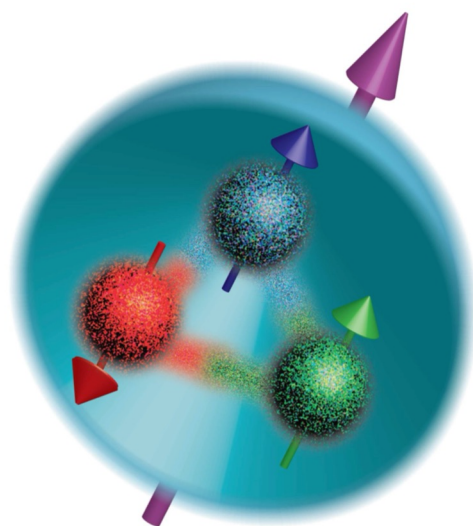


核子自旋结构的第一性原理研究



张其安

北京航空航天大学

On behalf of Lattice Parton Collaboration (LPC)

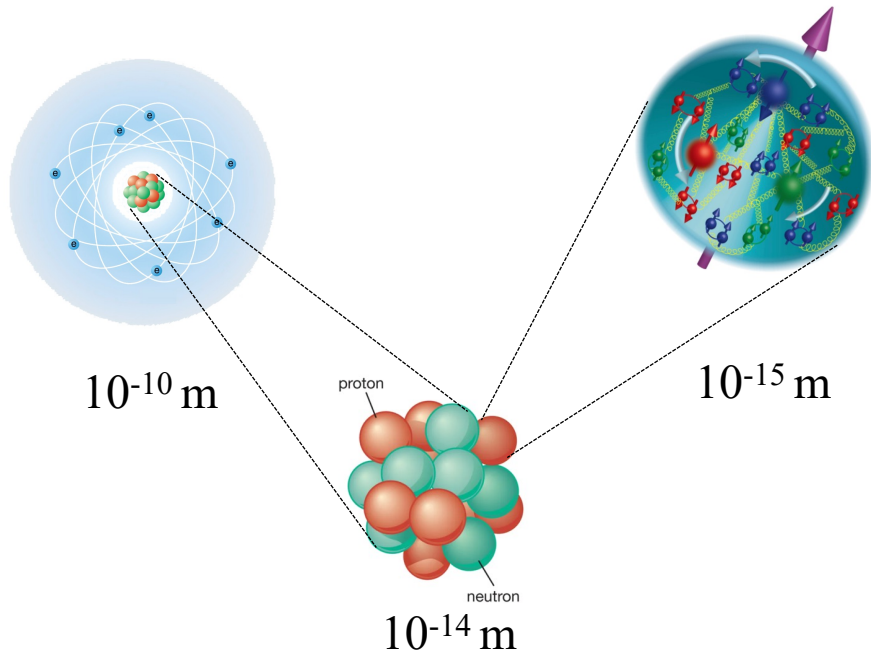
Aug. 13, 2026 @ 第十一届手征有效场论研讨会, 兰州

OUTLINE

- Motivation
- Polarized PDF Ratio: Spin Alignment of Quarks
- Quark TMDPDFs: 3D Momentum Tomography of Nucleon
- AI for Lattice QCD
- Summary and Outlook

Nucleons: Building Blocks of the Visible Universe

Despite more than half a century of exploration, the nucleon is still a very mysterious object, and the most abundant piece of matter in the visible Universe

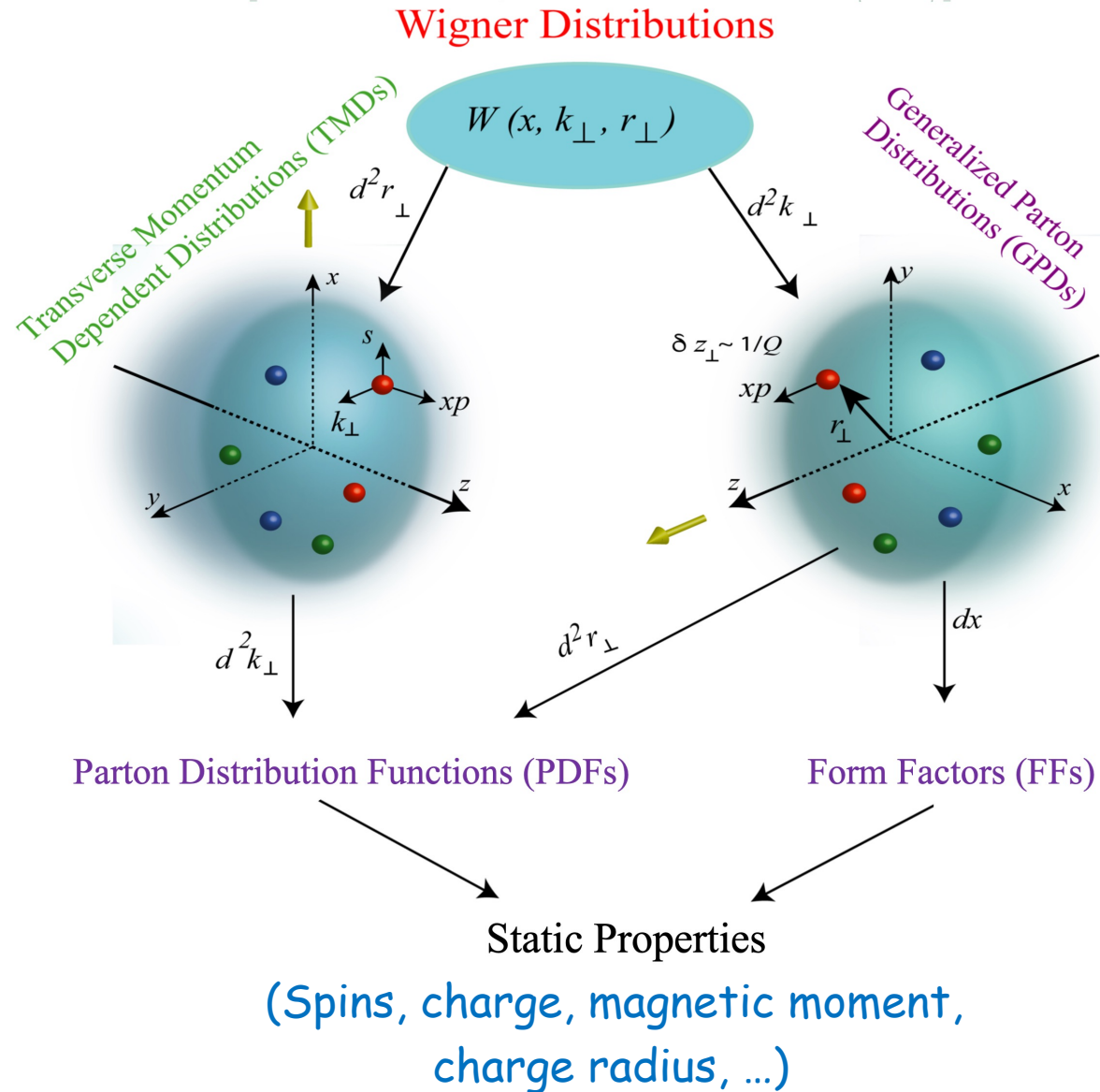


- How do quarks & gluons form the nucleon, how do they distribute?
- How do these distributions and partonic orbital motion generate the nucleon spin?

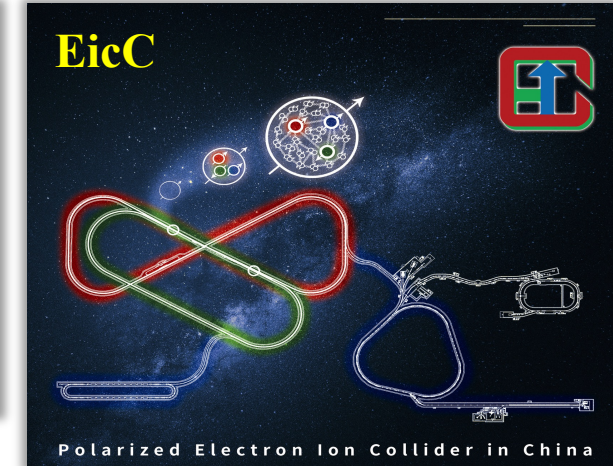
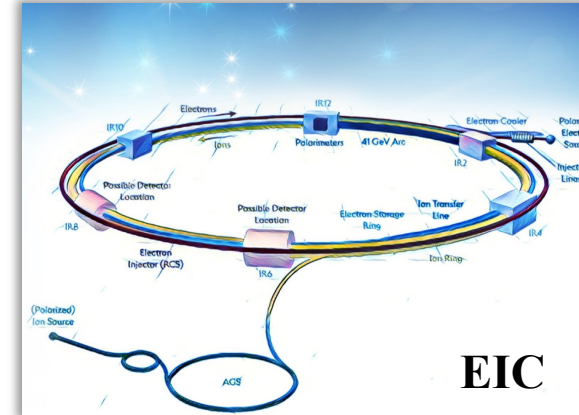
— *1st of the 3 central science questions driving the EIC program.*

Adapted from the White Paper of EIC, EPJA52, 268 (2016).

The Landscape of Nucleon Structure



- **3D Structures: TMDs and GPDs**

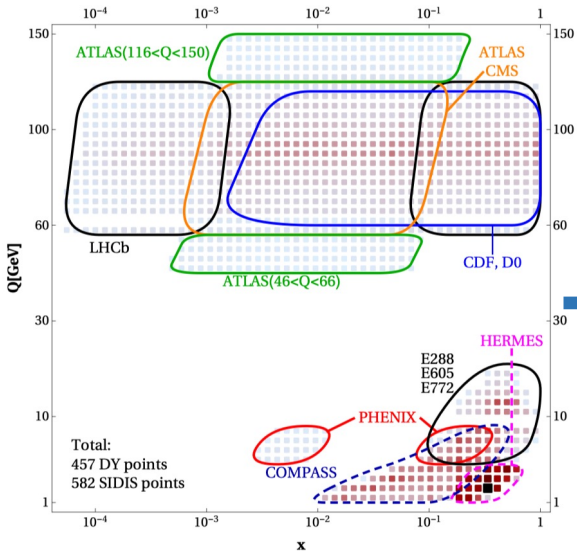


- 1D Structure: PDFs



How do we access the Nucleon Structures?

Exp.



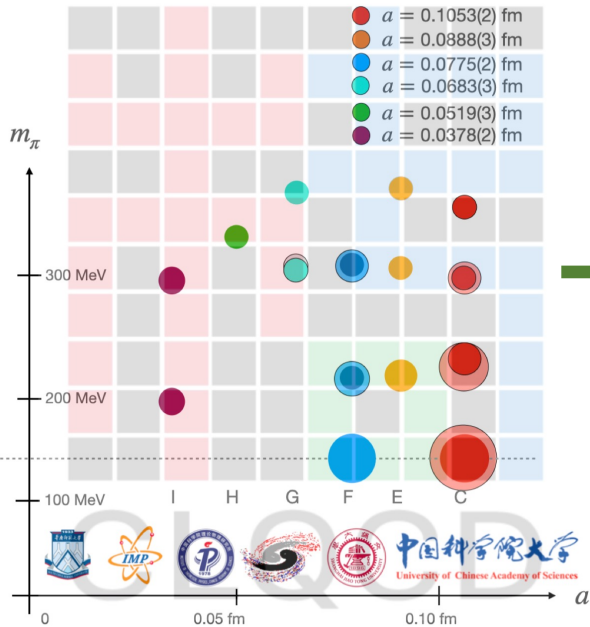
Cross Sections, asymmetries, ...

Global Analysis / Fitting

$$\chi^2 = \sum_i^{N_{\text{meas}}} \frac{(O_i - E_i)^2}{E_i}$$

Parameters

Lat.



Correlation Function

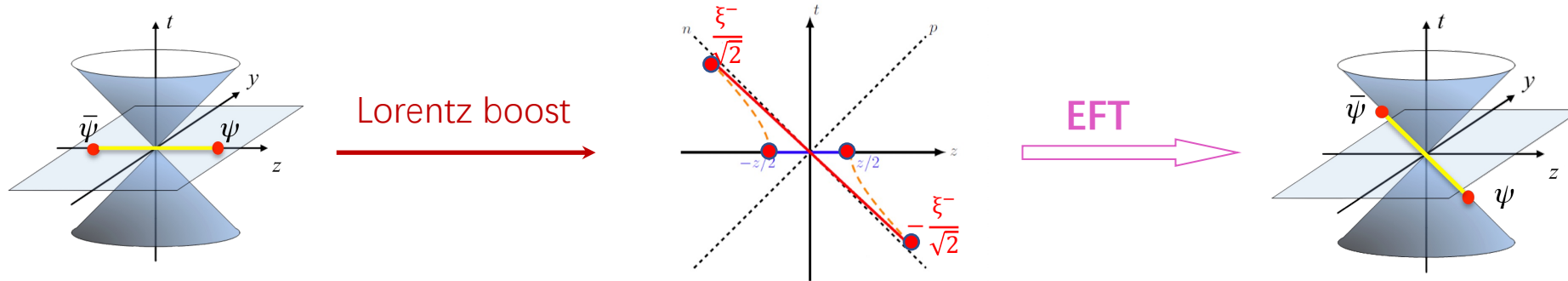
Effective Theory

$$\langle \tilde{O} \rangle_{\text{lat.}} = C \otimes \langle O \rangle_{l.c.}$$

Distributions

LaMET: A New Horizon for Nucleon Structure from Lattice

Large-momentum effective theory (LaMET): connecting Euclidean lattice and physical observables



Ji, PRL110, 262002 (2013), see Rev.Mod.Phys.93, 035005 (2021) for review

- Equal-time distributions can be directly computed in lattice QCD:

$$\tilde{q}(x, P^z) = \int \frac{dz}{2\pi} e^{-izP^z} \langle P^z | \bar{\psi}(z) \Gamma \mathcal{U}(z, 0) \psi(0) | P^z \rangle$$

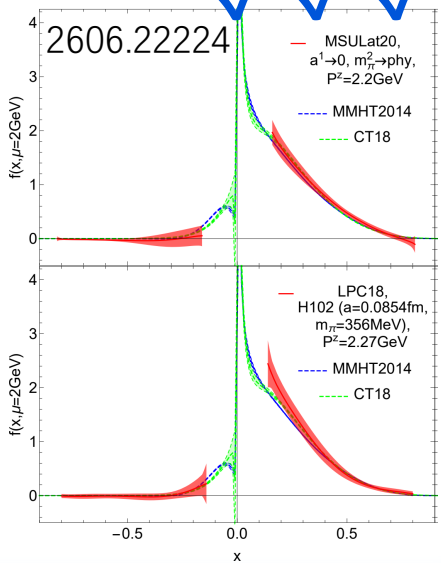
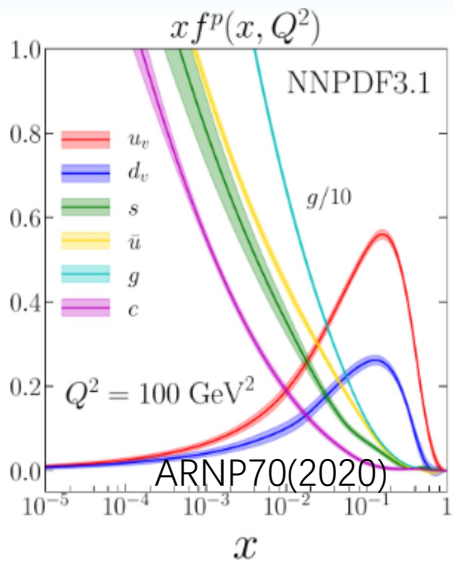
- Recovering light-cone distributions in the large-momentum limit:

$$q(y, \mu) = \int_{-\infty}^{+\infty} \frac{dx}{|x|} c\left(\frac{y}{x}, \frac{\mu}{xP^z}\right) \tilde{q}(x, P^z) + \mathcal{O}\left(\frac{M^2}{(\mathbf{P}^z)^2}, \frac{\Lambda_{\text{QCD}}^2}{(yP^z, (1-y)P^z)^2}\right)$$

Status of the 1D & 3D Nucleon Structure

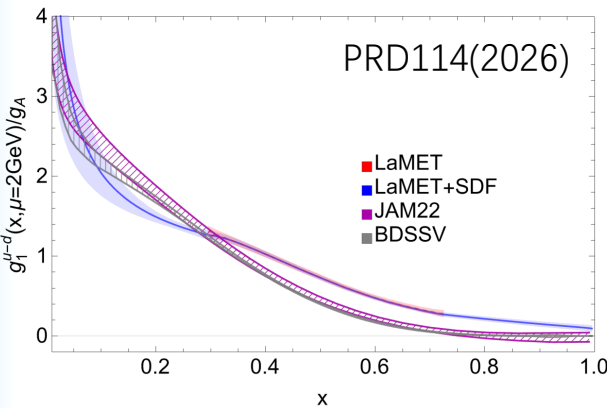
Unpolarized

1D

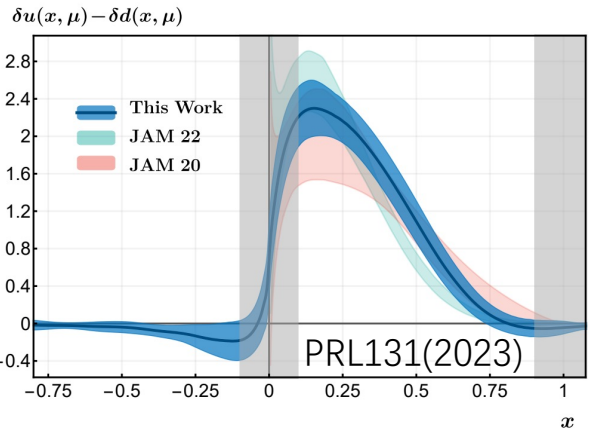


Polarized

Helicity PDF (lat. vs fit)

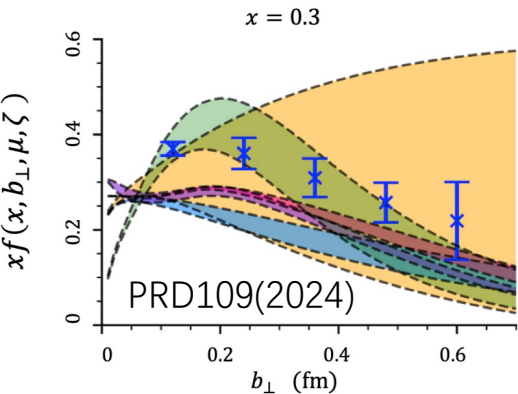


Transversity PDF (lat. vs fit)

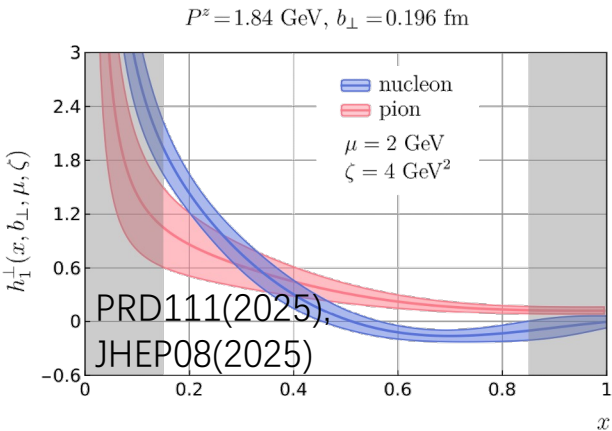


3D

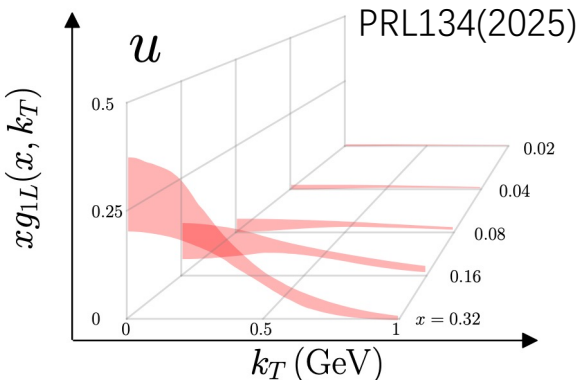
Unpolarized TMDPDF (lat. vs fit)



Boer-Mulders function (lat.)



Transversity TMDPDF (fit)

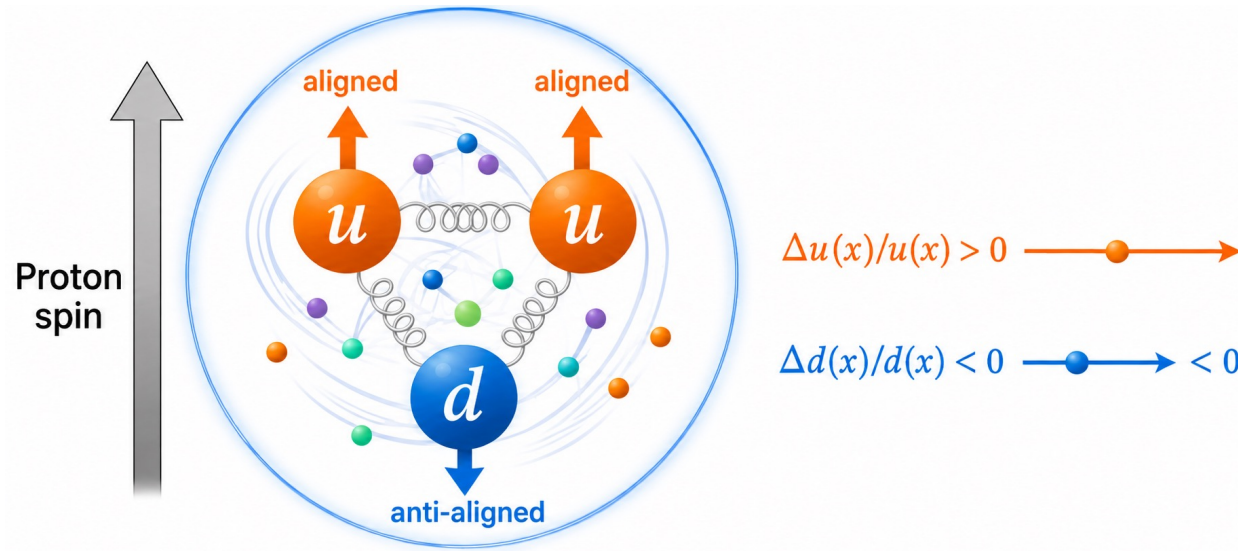


.....

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Spin Alignment of the Quarks



- Quark helicity PDF:

$$\Delta q(x) = q^\uparrow(x) - q^\downarrow(x)$$

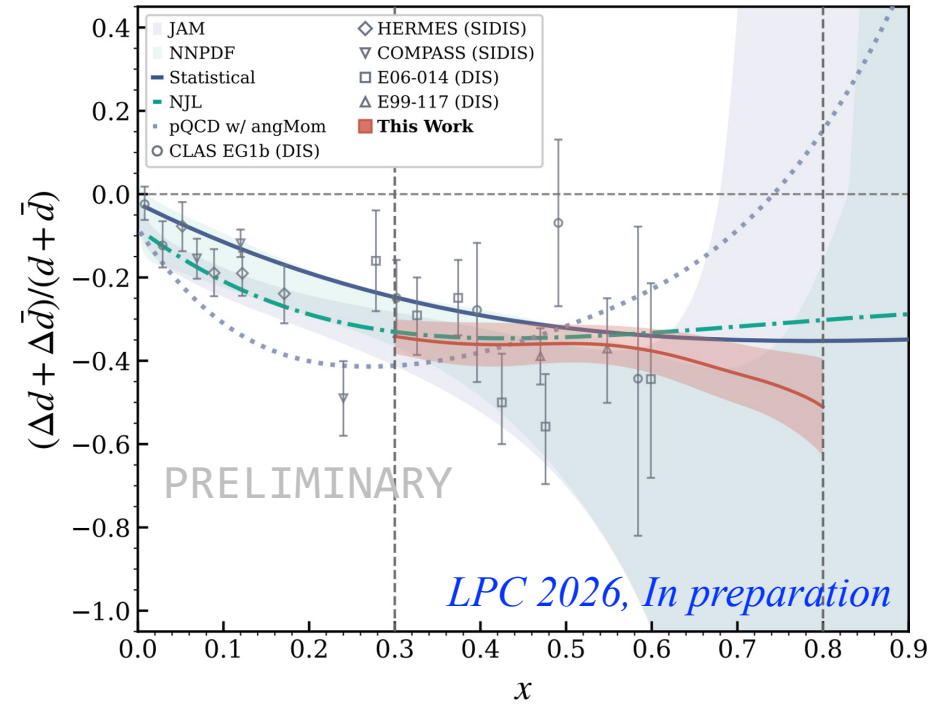
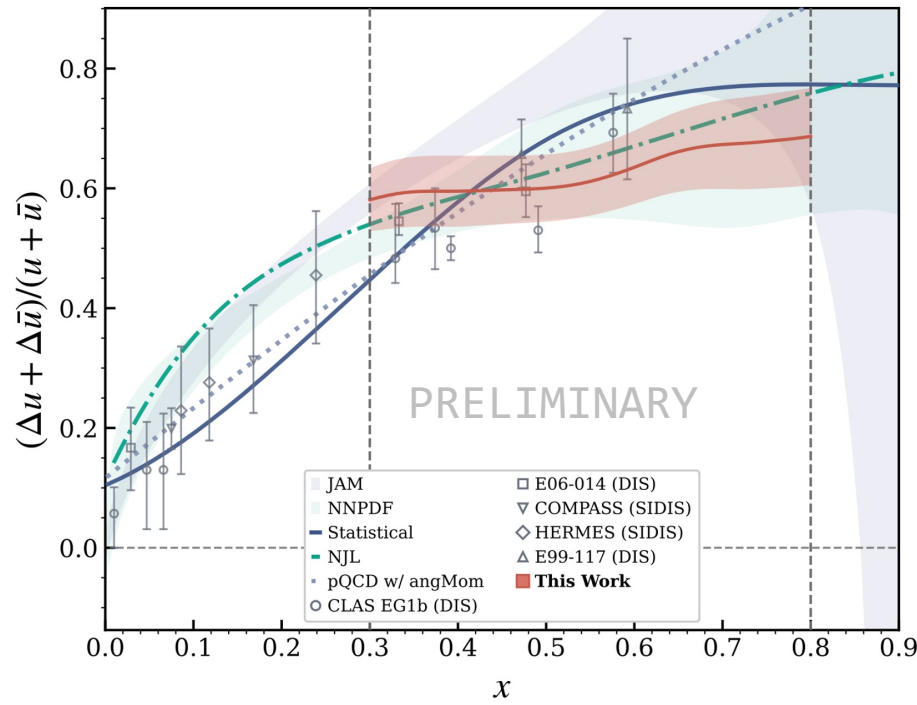
- Quark unpolarized PDF:

$$q(x) = q^\uparrow(x) + q^\downarrow(x)$$

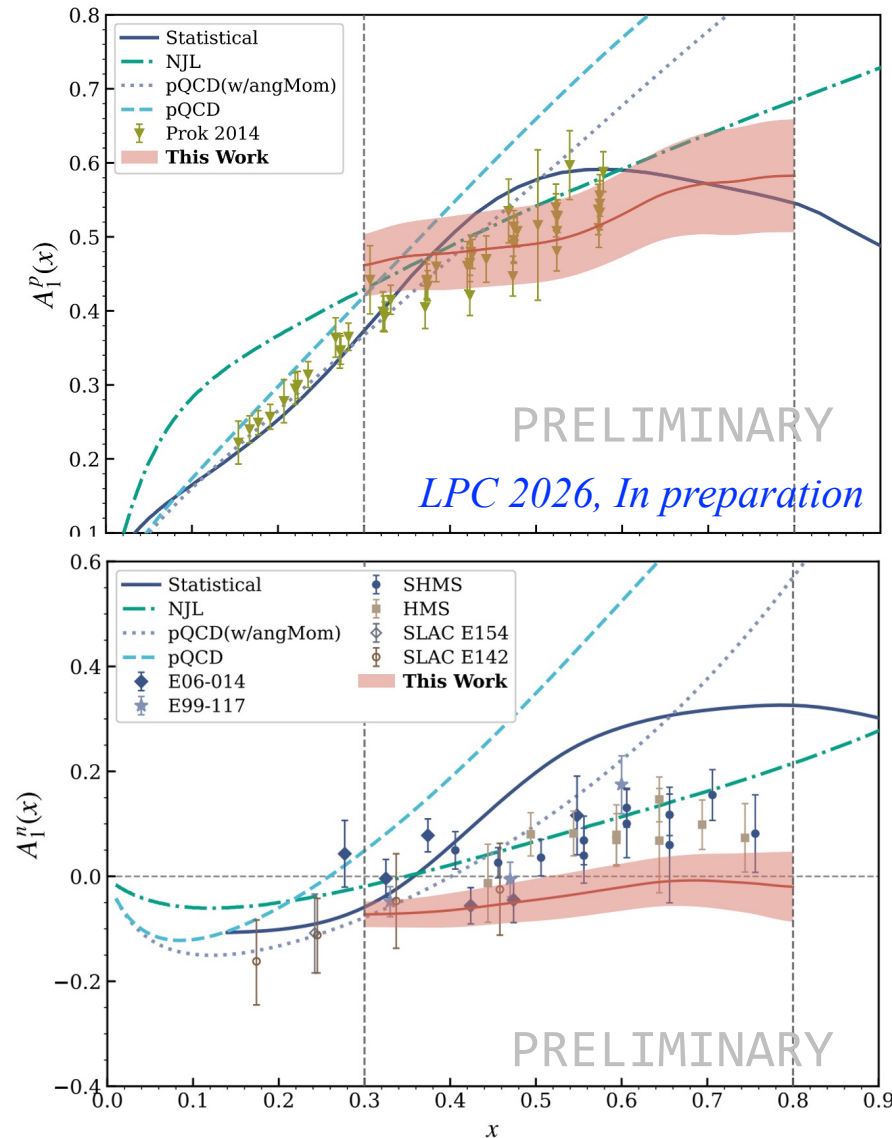
$\Delta q(x)/q(x)$ encodes the longitudinal spin alignment of quarks inside the proton, providing a clean probe of its spin-flavor structure

Ratios of Polarized PDFs from Lattice QCD

- u -quark polarization ratio is positive and rises with x
- d -quark polarization ratio remains negative throughout the accessible x region



Predictions for Nucleon Spin Asymmetries



- A_1 is the ratio between polarized structure function g_1 and unpolarized structure function F_1 :

$$A_1^N(x, Q^2) \simeq \frac{g_1^N(x, Q^2)}{F_1^N(x, Q^2)}$$

- Neglecting the strange quark, sea quark flavor separation and higher-twist corrections, the proton and neutron asymmetries:

$$A_1^p(x) \simeq \frac{4\Delta u(x) + \Delta d(x)}{4u(x) + d(x)},$$

$$A_1^n(x) \simeq \frac{\Delta u(x) + 4\Delta d(x)}{u(x) + 4d(x)}.$$

Y. Prok et al. (CLAS), PRC 90, 025212 (2014).

D. Flay et al. (JLab Hall A), PRD 94, 052003 (2016).

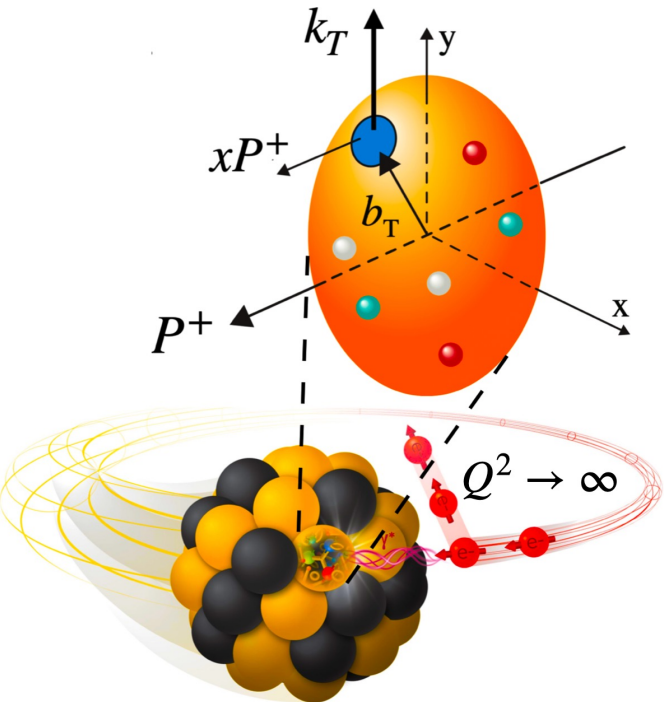
X. Zheng et al. (JLab Hall A), PRL 92, 012004 (2004);

X. Zheng et al., PRC 70, 065207 (2004).

OUTLINE

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TMDs: 3D Momentum Tomography of Nucleon



TMDs: Spin-dependent 3D momentum space images from semi-inclusive scattering

Leading Quark TMDPDFs

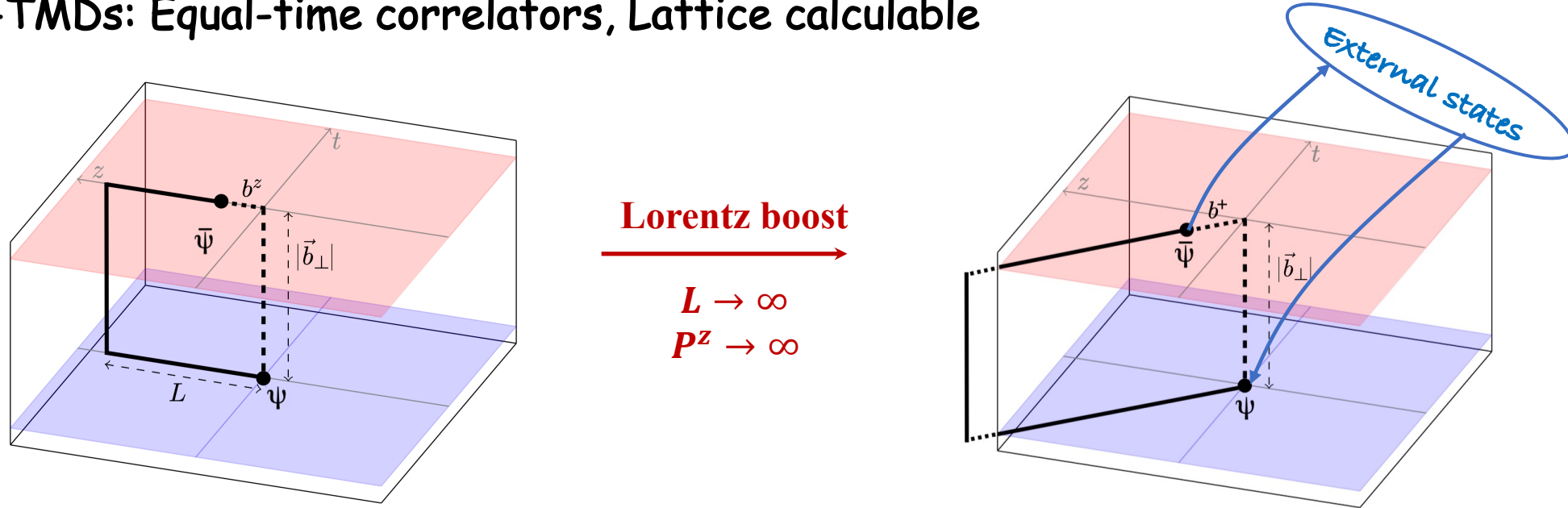
Nucleon Spin

Quark Spin

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \text{Unpolarized}$		$h_1^\perp = \text{Boer-Mulders}$
	L		$g_1 = \text{Helicity}$	$h_{1L}^\perp = \text{Worm-gear}$
	T	$f_{1T}^\perp = \text{Sivers}$	$g_{1T}^\perp = \text{Worm-gear}$	$h_1 = \text{Transversity}$ $h_{1T}^\perp = \text{Pretzelosity}$

TMDs from Lattice QCD within LaMET

Quasi-TMDs: Equal-time correlators, Lattice calculable



Factorization in LaMET:

PLB811, 135946 (2020); JHEP04, 178, (2022)

Perturbative matching kernel

$$\tilde{f}_\Gamma(x, b_\perp, \mu, \zeta^z) \sqrt{S_I(b_\perp, \mu)} = H_\Gamma(\zeta^z, \mu) \exp\left[\frac{1}{2} K(b_\perp, \mu) \ln \frac{\zeta^z}{\zeta}\right] f(x, b_\perp, \mu, \zeta) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{\zeta^z}, \frac{M^2}{(P^z)^2}, \frac{1}{b_\perp^2 \zeta^z}\right)$$

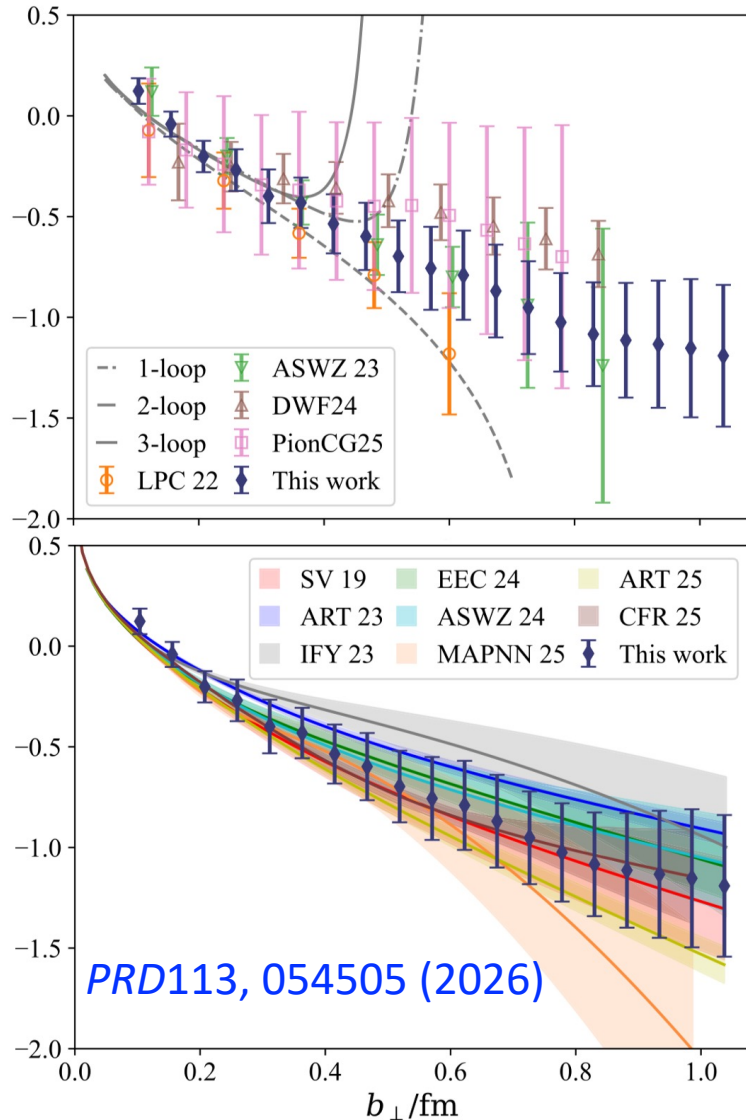
Quasi TMDs

Intrinsic Soft Function

Collins-Soper kernel

Light-cone TMDs

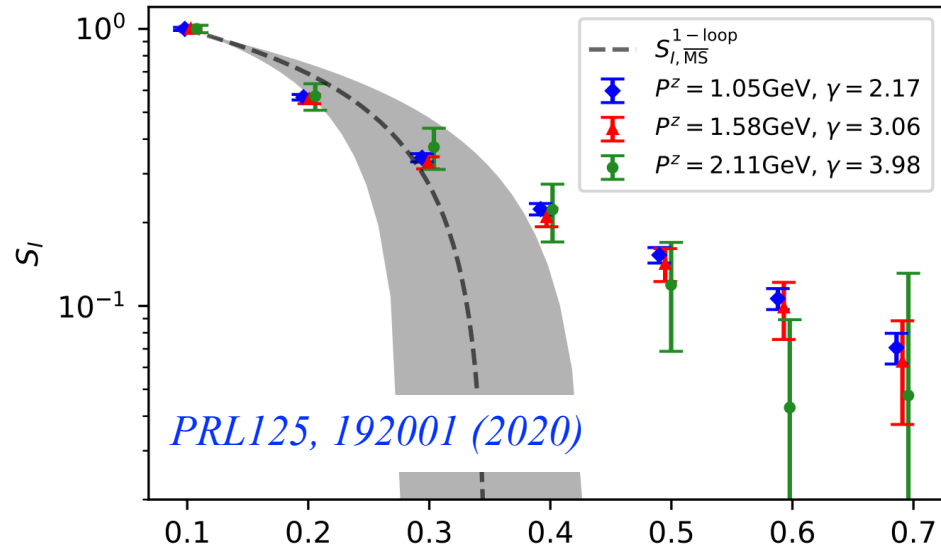
Collins-Soper Kernel from Lattice QCD



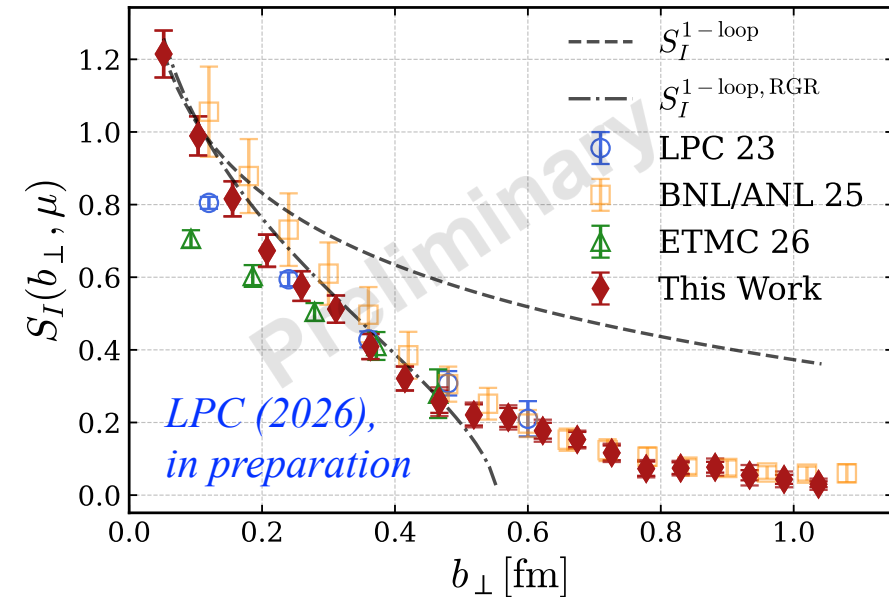
- A benchmark quantity for lattice TMD studies
 - ✓ Continuum, physical mass, and infinite-momentum limits are now being addressed
 - ✓ Lattice QCD provides first-principles constraints up to $b_T \sim 1\text{fm}$
 - ✓ Agreement with global fits provides mutual validation
- A precise CS kernel is a key step toward first-principles predictions of TMD observables

Intrinsic Soft Function from Lattice QCD

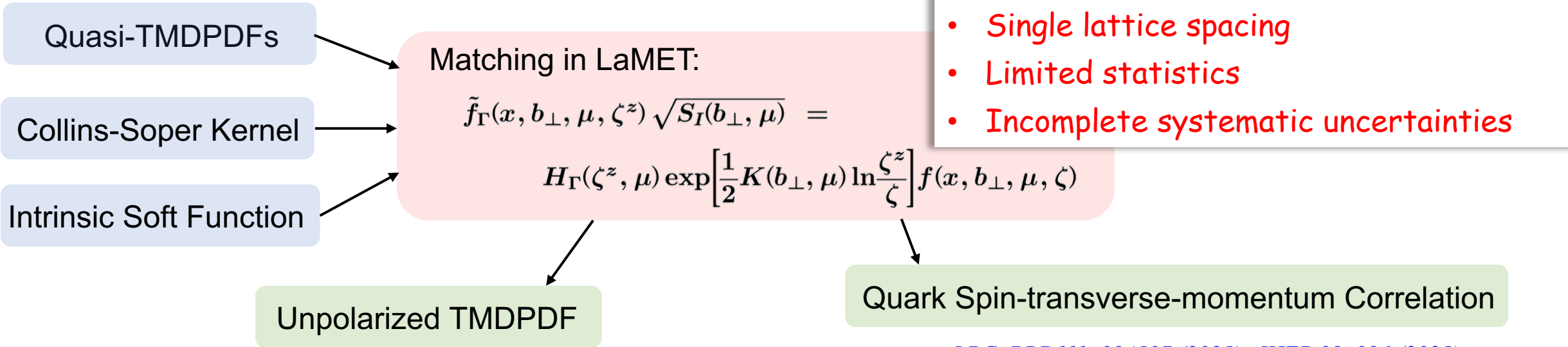
LPC, 2020



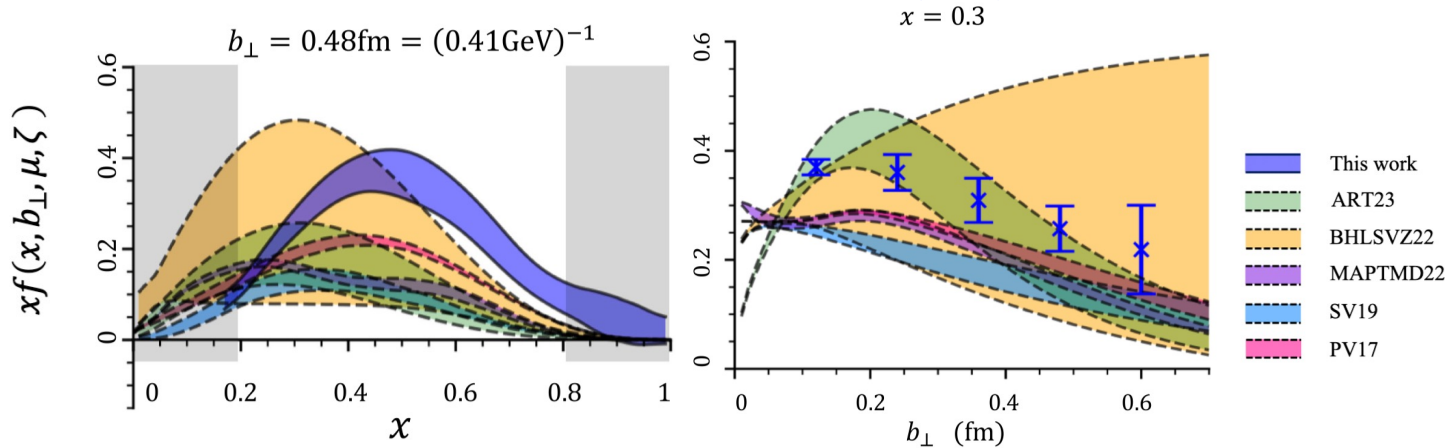
LPC, 2026



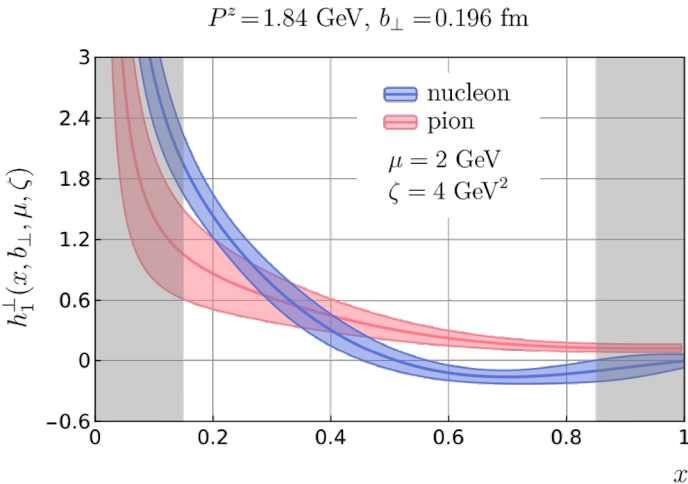
- ✓ Continuum, physical mass and infinite-momentum limits
- ✓ Precise first-principles prediction up to $b_T \sim 1\text{fm}$
- ✓ Essential input for the lattice calculation of TMDPDFs



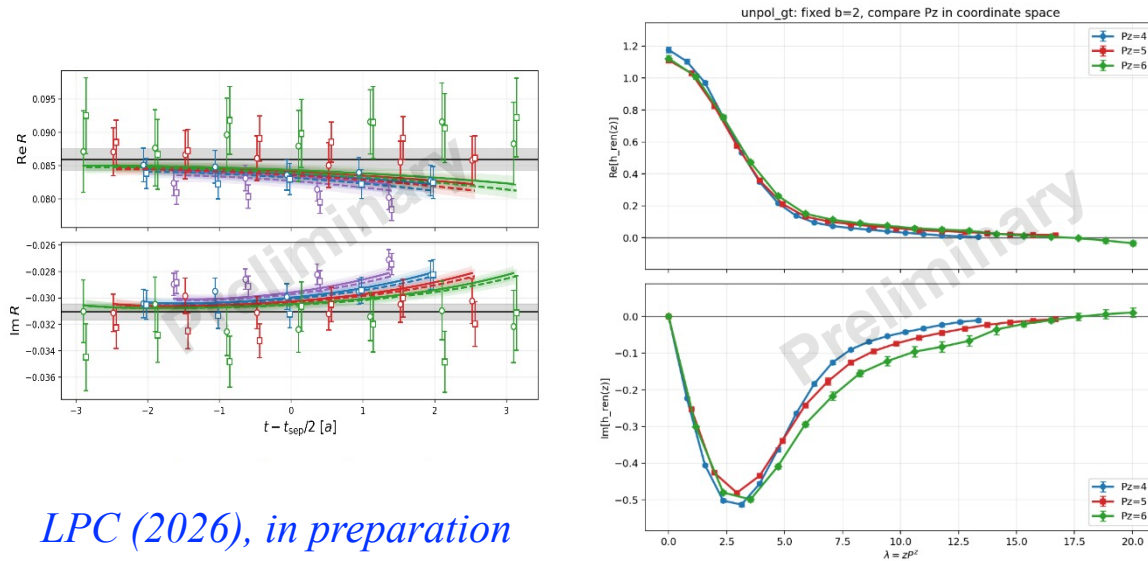
LPC, PRD109, 114513 (2024)



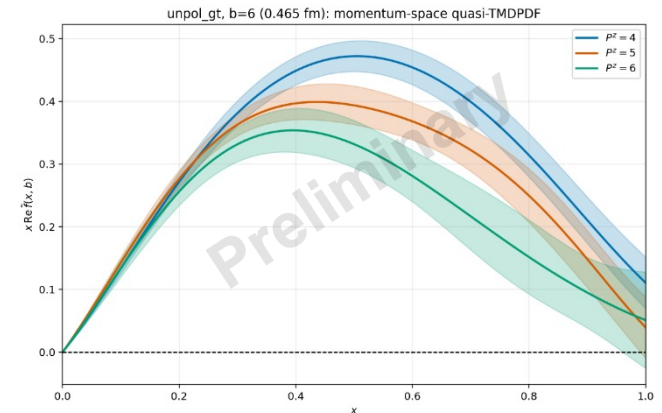
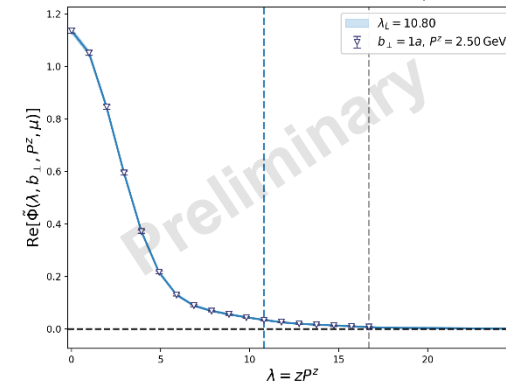
LPC, PRD111, 094507 (2025); JHEP 08, 086 (2025)



- E.g.: Unpolarized TMDPDF



- ✓ Multi lattice spacings $\Rightarrow$ Continuum Limit
- ✓ Multi pion masses $\Rightarrow$ Chiral Limit
- ✓ Large statistics



Ground-state fit
the ratio of 3pt/2pt

Nonlocal renormalization
to get coordinate-space
distribution

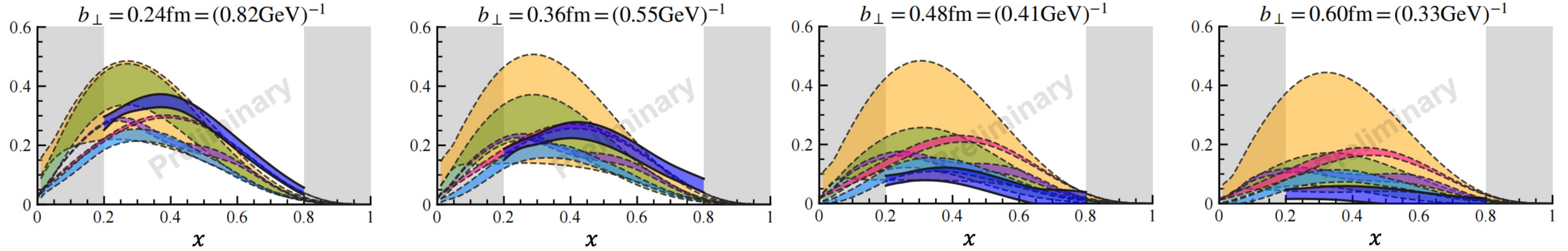
Large- λ
extrapolation

Fourier transform to get
momentum-space
quasi-TMDPDF

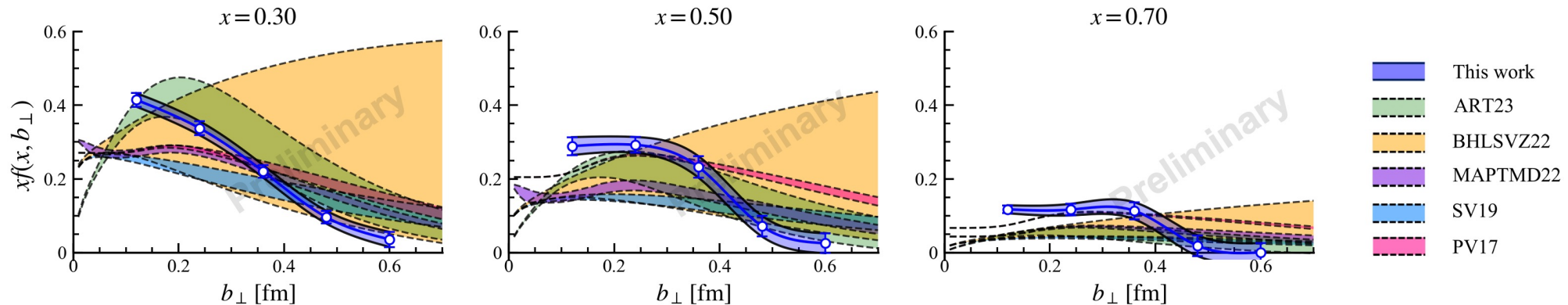
Unpolarized TMDPDFs from Lattice QCD

- x-dependence

LPC (2026), in preparation



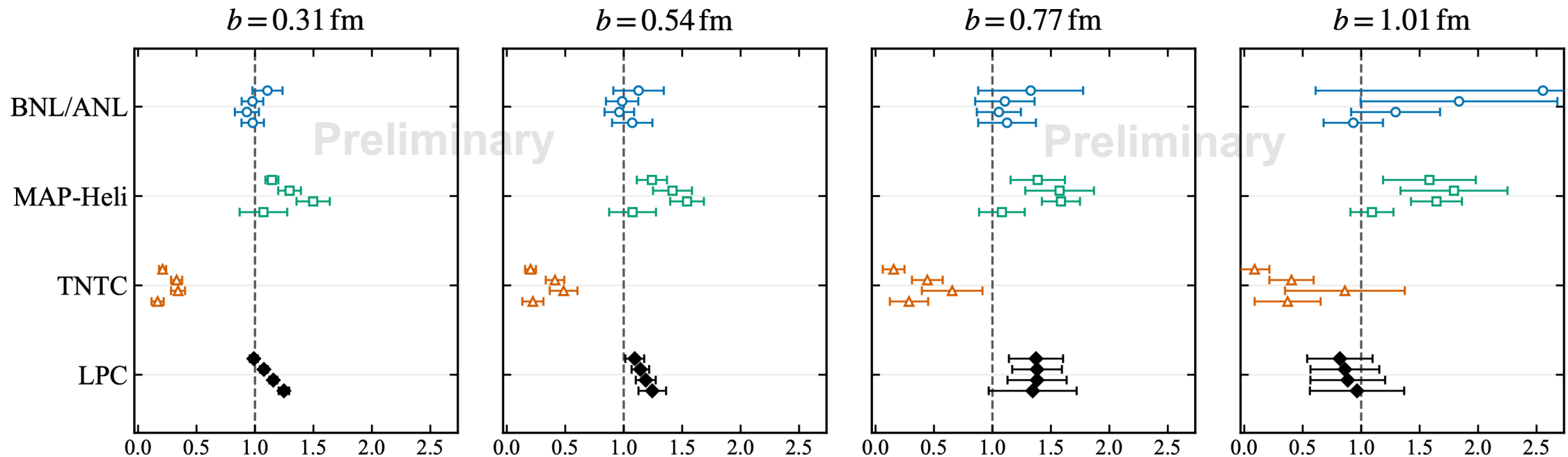
- $b_\perp$ -dependence



Spin Alignment in TMDs

- Helicity-to-Unpolarized TMD Ratio:

LPC (2026), in preparation



- More systematic analyses are in progress

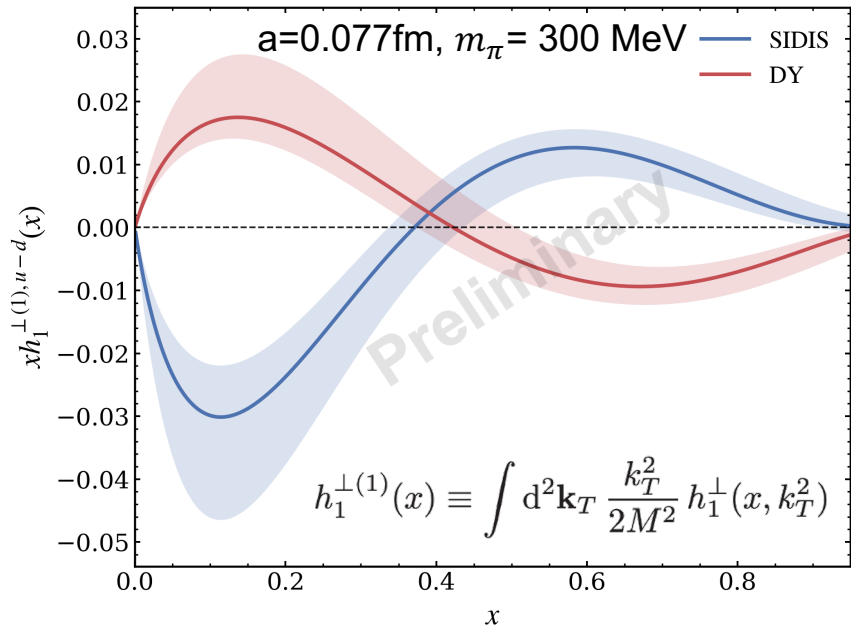
BNL/ANL (LQCD): PRL135, 20 (2025)
MAP (Global fit): PRL134, 121901 (2025)
TNTC (Global fit): PRL134, 121902 (2025)

Quark Spin-transverse-momentum Correlation

- First moment of quasi Boer-Mulders function and its matching

$$\tilde{h}_1^{\perp(1)}(x, b_\perp^2, P^z, \mu) = \frac{1}{iM\epsilon_\perp^{ij}b_{\perp j}} \frac{E}{P^z} \int \frac{dz}{2\pi} e^{ixP^z z} \frac{\sum_S \text{Tr} \left[P_+ u(P, S) \langle N(P, S) | O^{i\sigma^\perp z} \gamma_5(z, b_\perp) | N(P, S) \rangle \bar{u}(P, S) \right]_R}{\sum_S \text{Tr} [P_+ u(P, S) \bar{u}(P, S)]_R}$$

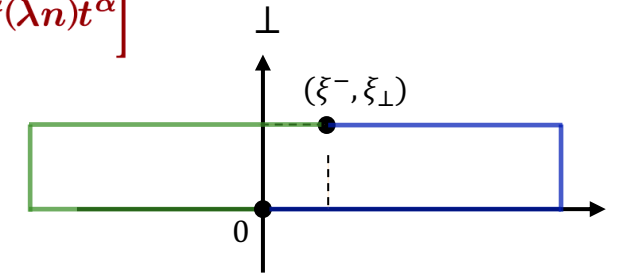
$$\tilde{h}_1^{\perp(1)}(x, b_\perp^2, P^z, \mu) \sqrt{S_I(b_\perp, \mu)} = \exp \left[\frac{1}{2} \ln \frac{\zeta_z}{\zeta} K(b_\perp, \mu) \right] H \left(\frac{x}{y}, \frac{\mu^2}{\zeta_z} \right) h_1^{\perp(1)}(y, b_\perp^2, \mu, \zeta) + \mathcal{O} \left(\frac{\Lambda_{\text{QCD}}^2}{\zeta_z}, \frac{M^2}{(P^z)^2}, \frac{1}{b_\perp^2 \zeta_z} \right)$$



- Gauge links generate initial and final state interactions and distinguish the SIDIS & Drell-Yan processes

$$\mathcal{U}_n(a, b) = \exp \left[-ig \int_a^b d\lambda n \cdot A^\alpha(\lambda n) t^\alpha \right]$$

LPC (2026), in preparation



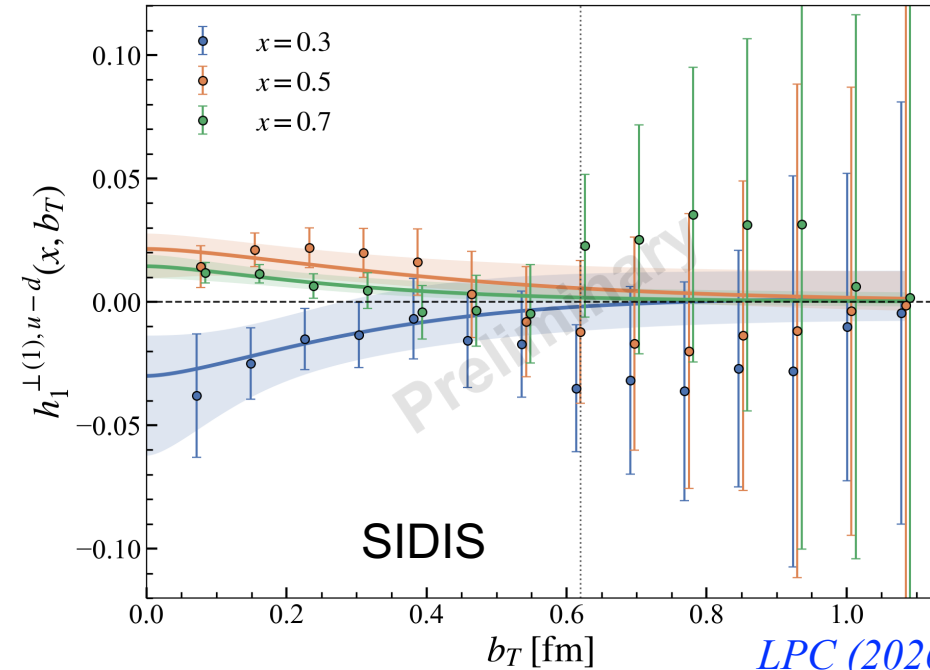
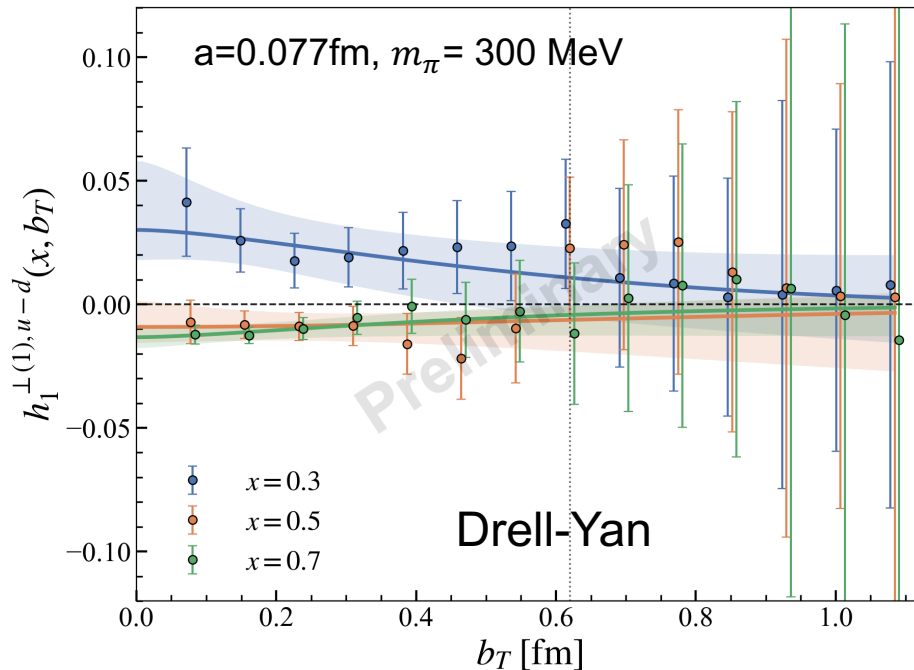
Quark Spin-transverse-momentum Correlation

- Rebuild the full distribution of $h_1^\perp(x, k_\perp^2)$ from model parametrization

Bacchetta, Conti, Radici, PRD78, 074010 (2008)

$$h_1^{\perp, u-d}(x, k_\perp^2) = \frac{M_N^2}{2\pi k_\perp} \int db_\perp b_\perp^2 J_1(k_\perp b_\perp) h_1^{\perp(1)}(x, b_\perp^2)$$

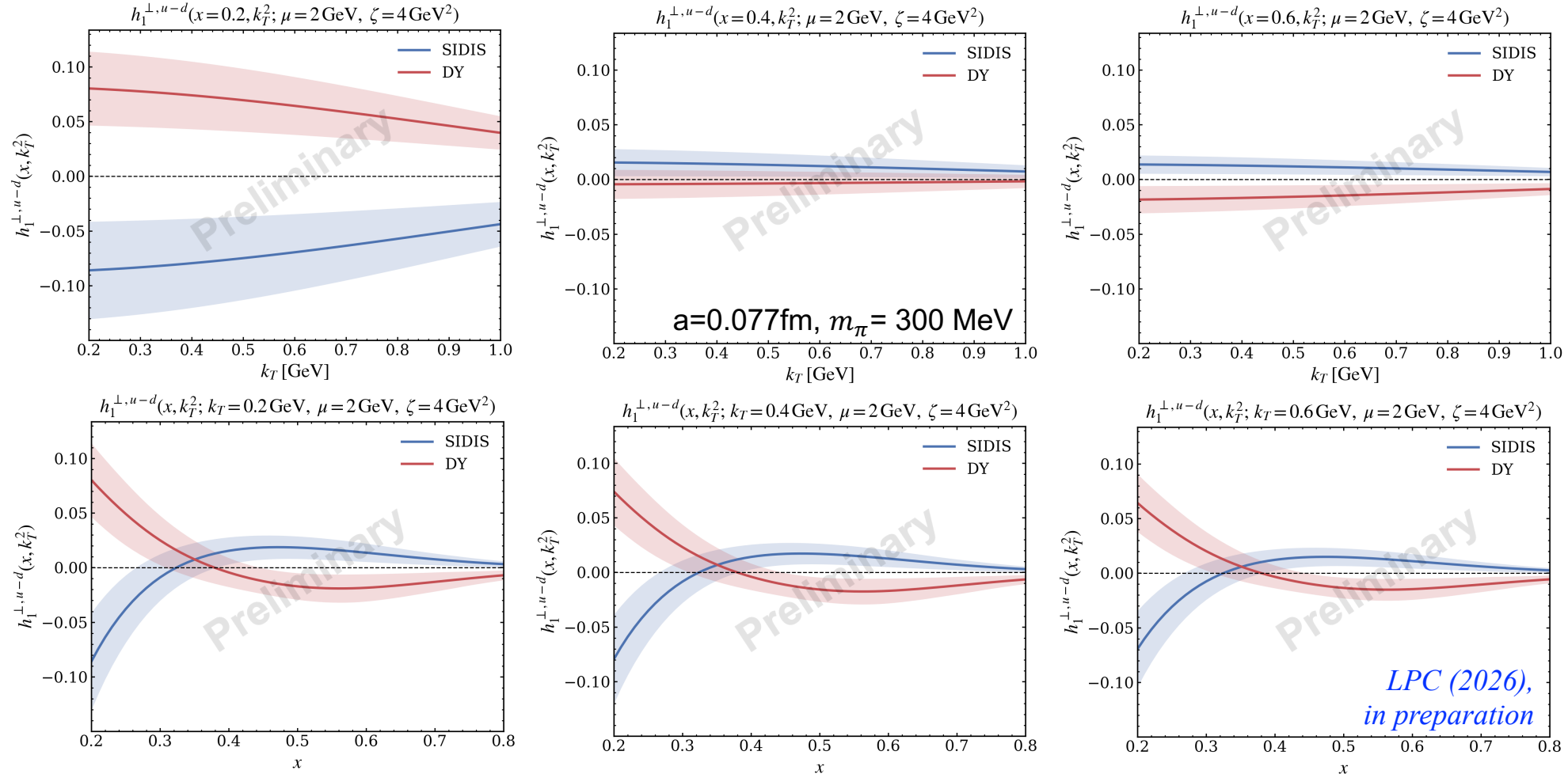
$$\equiv H_S(x) \frac{4M^2}{\pi L_S^4(x)} \left(1 + \frac{k_\perp^2}{L_S^2(x)}\right)^{-3} - H_A \frac{4M^2}{\pi L_A^4(x)} \left(1 + \frac{k_\perp^2}{L_A^2(x)}\right)^{-3}$$



LPC (2026), in preparation

Quark Spin-transverse-momentum Correlation

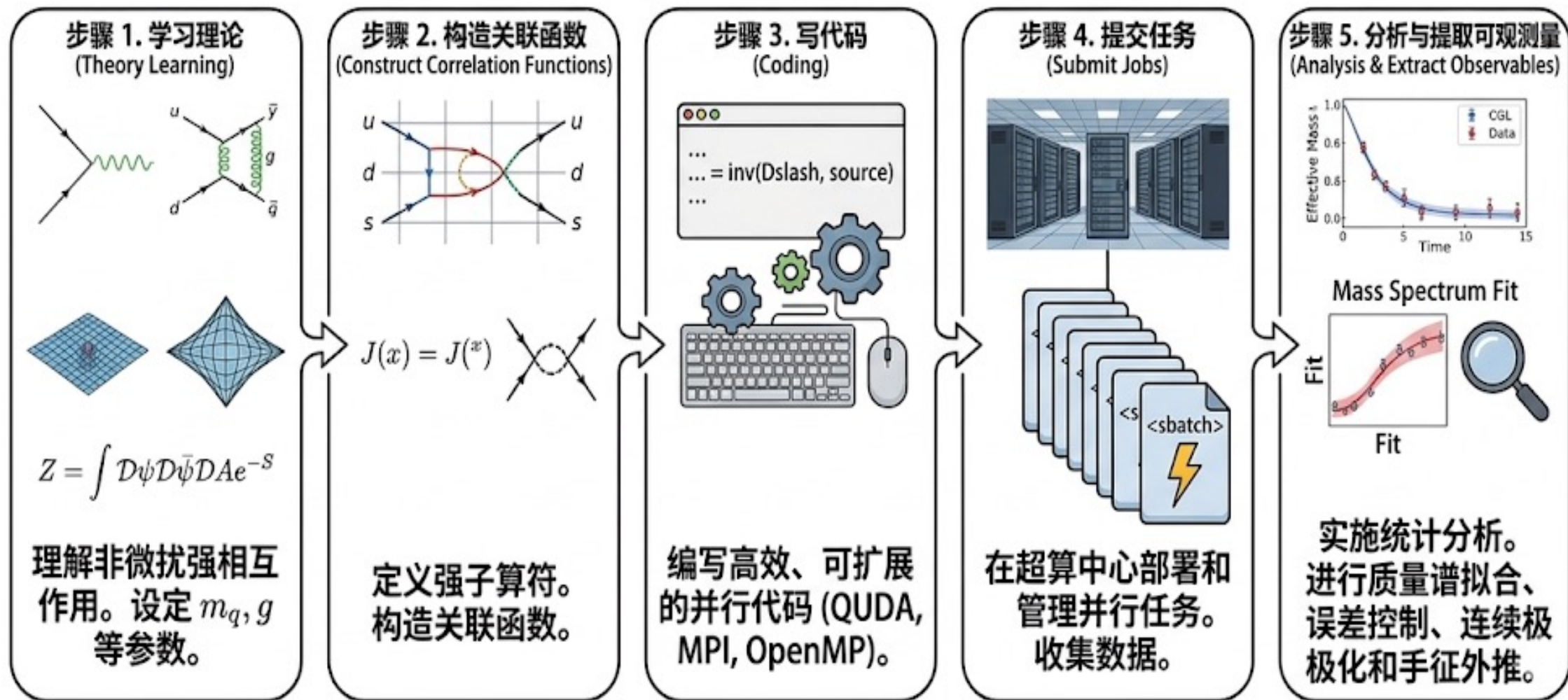
- Rebuild the full distribution of $h_1^\perp(x, k_\perp^2)$ from model parametrization



OUTLINE

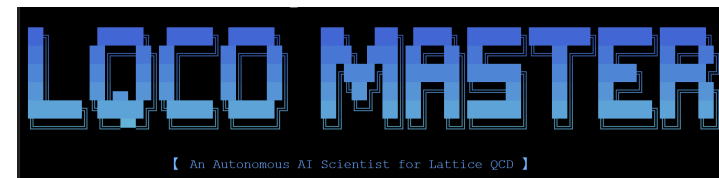
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Workflow for Lattice QCD



✓ 计算：物理目标 → 计算程序

- 必要的物理知识：量子场论，算符构造，关联函数，...
- 专业的计算程序：Chroma，PyQUDA，...



✓ 分析：格点数据 → 物理结果

- 超长链条、海量数据、高维结构的复杂分析
- 耗时久，需至少两人检查

PhysMaster

2512.19799, PhysMaster
2603.22471, PhysMaster for LQCD
2604.15411, PRL-Bench
2607.15001, LQCDMaster



基于智能体的通用技术+工具增强+技能指导，我们设计了LQCDMaster智能体

✓ 3-step:

- Planner
- Executor
- Verifier

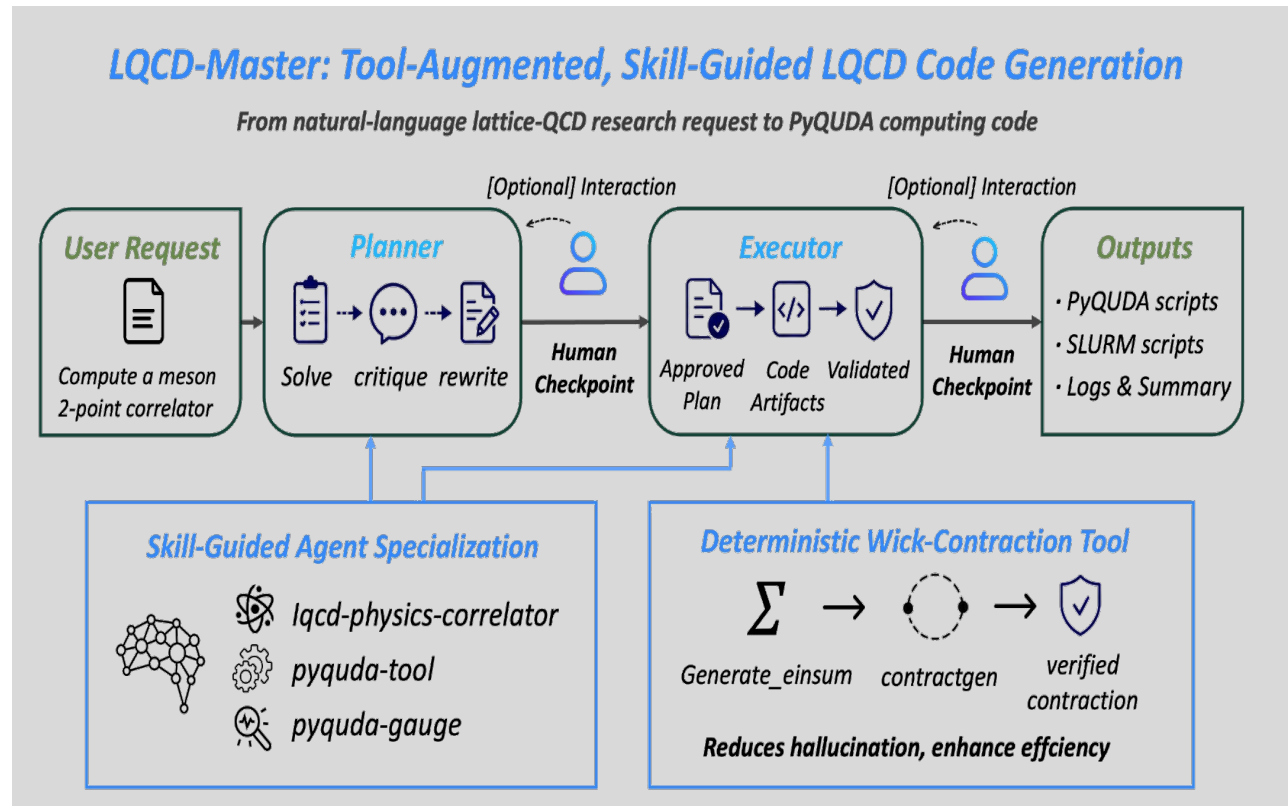
✓ Tool:

- Generate_einsum
- Contractgen

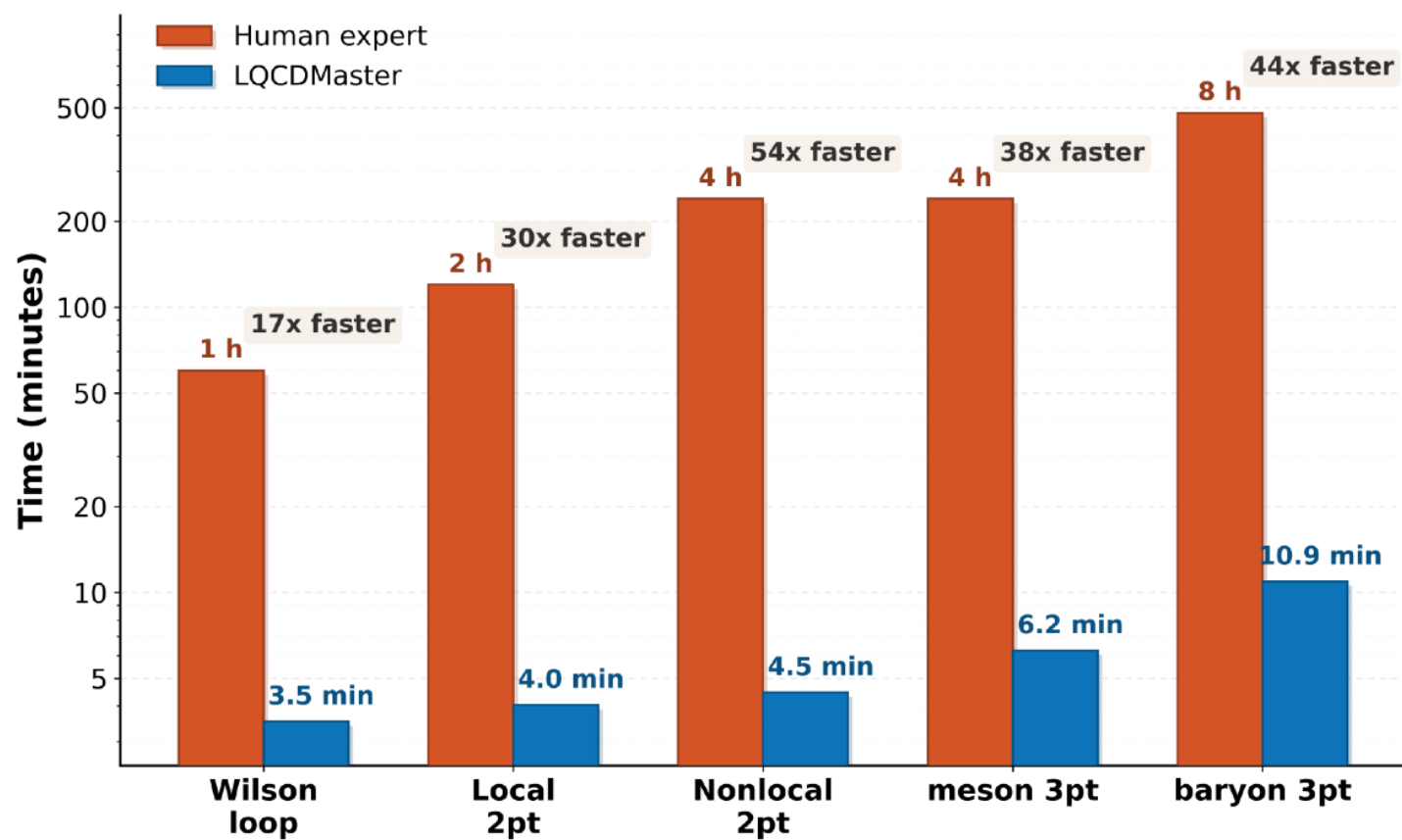
✓ Skill:

- lqcd-physics-correlator
- pyquda-tool
- Pyquda-gauge

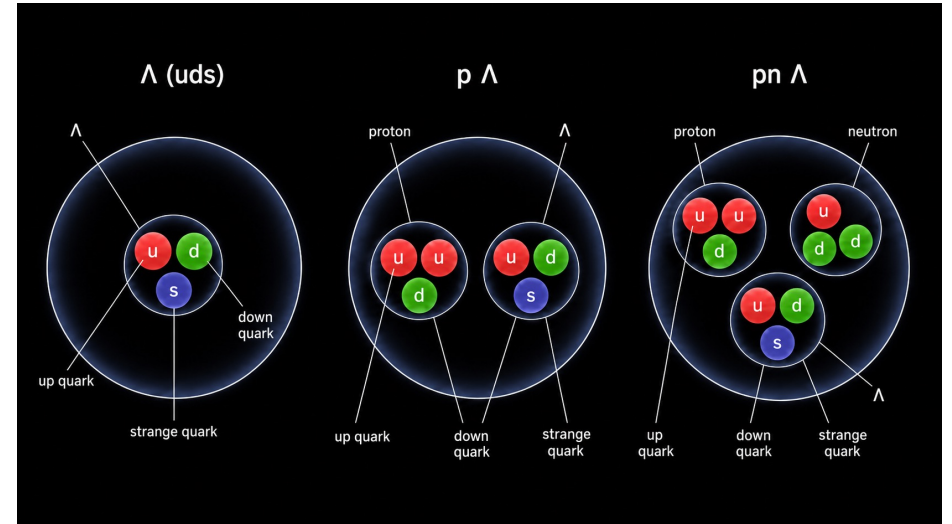
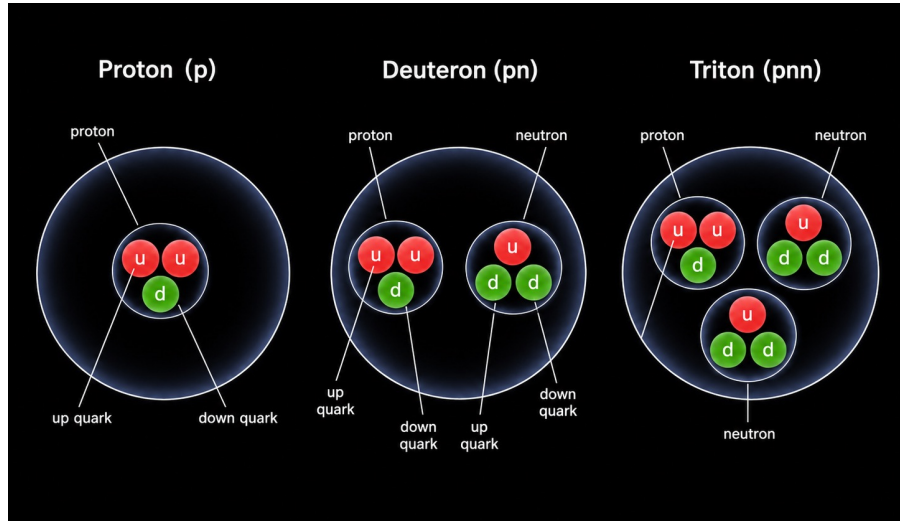
LQCDMaster的流程示意图 2607.15001



相较于人类专家， LQCDMaster可以实现17-54倍的提速！



LQCD calculation of lowest-lying nucleus



使用自然语言输入

Use `multi_hadron_2pt` to compute the combined two-baryon two-point function for a local 6-quark operator.

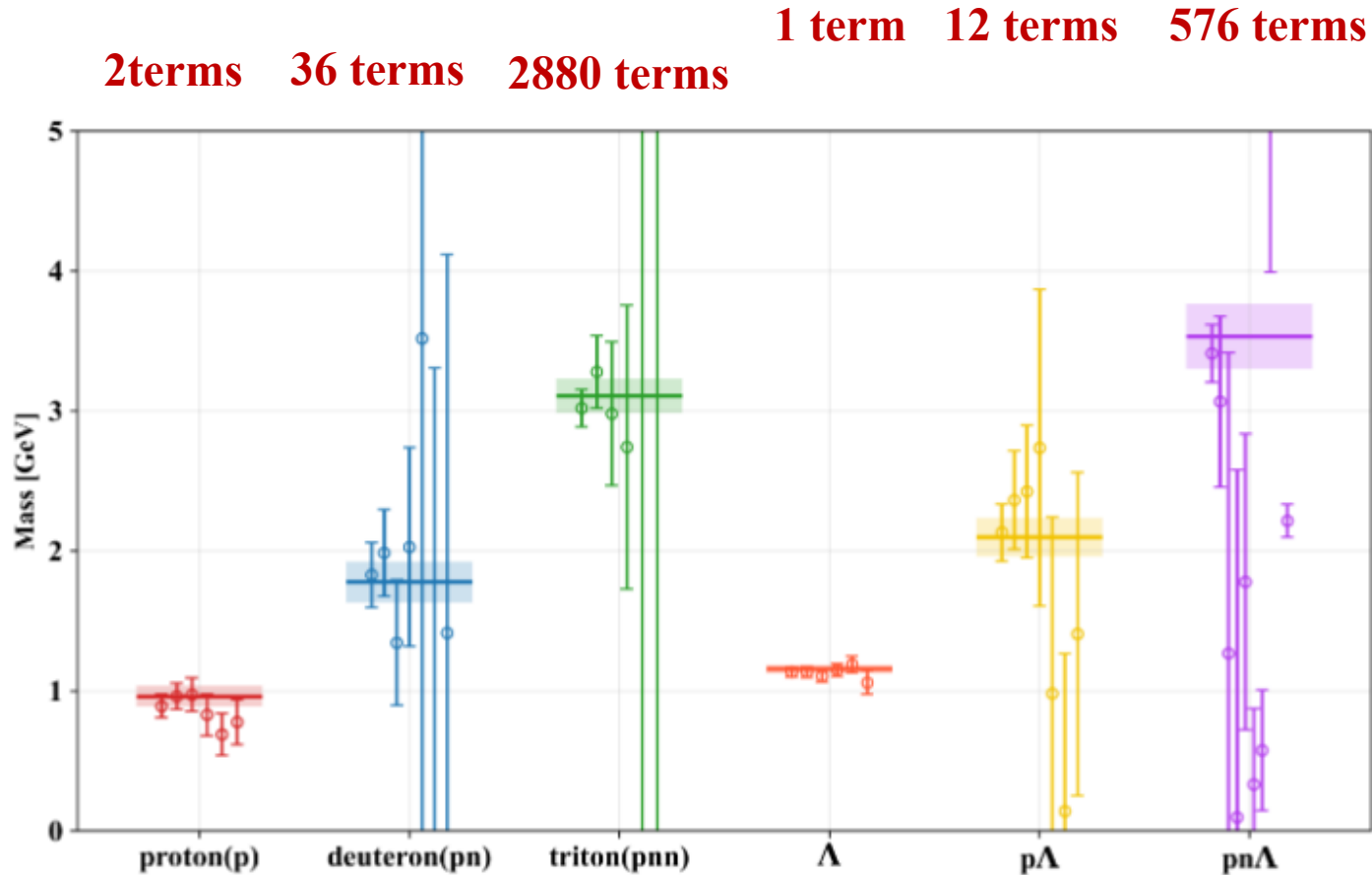
The combined interpolating operator at source and sink is:

$$O = (u^T C g_5 d) d * (u^T C g_5 d) u$$

Use single-term baryon operators only (no octet flavor combinations). Apply `P_plus` projector on each baryon block individually (per-baryon block projection, not composite-level). The contraction should be one multi-hadron 2pt object, NOT a product of separate baryon 2pt correlators.

Nuclear mass spectra with LQCDMaster finished within 10 minutes.

LQCD calculation of lowest-lying nucleus



LQCD for Nuclear Spectra:

- ✓ High theoretical complexity
- ✓ Predictions consistent with data
- ✓ Imprecise due to limited computational resources

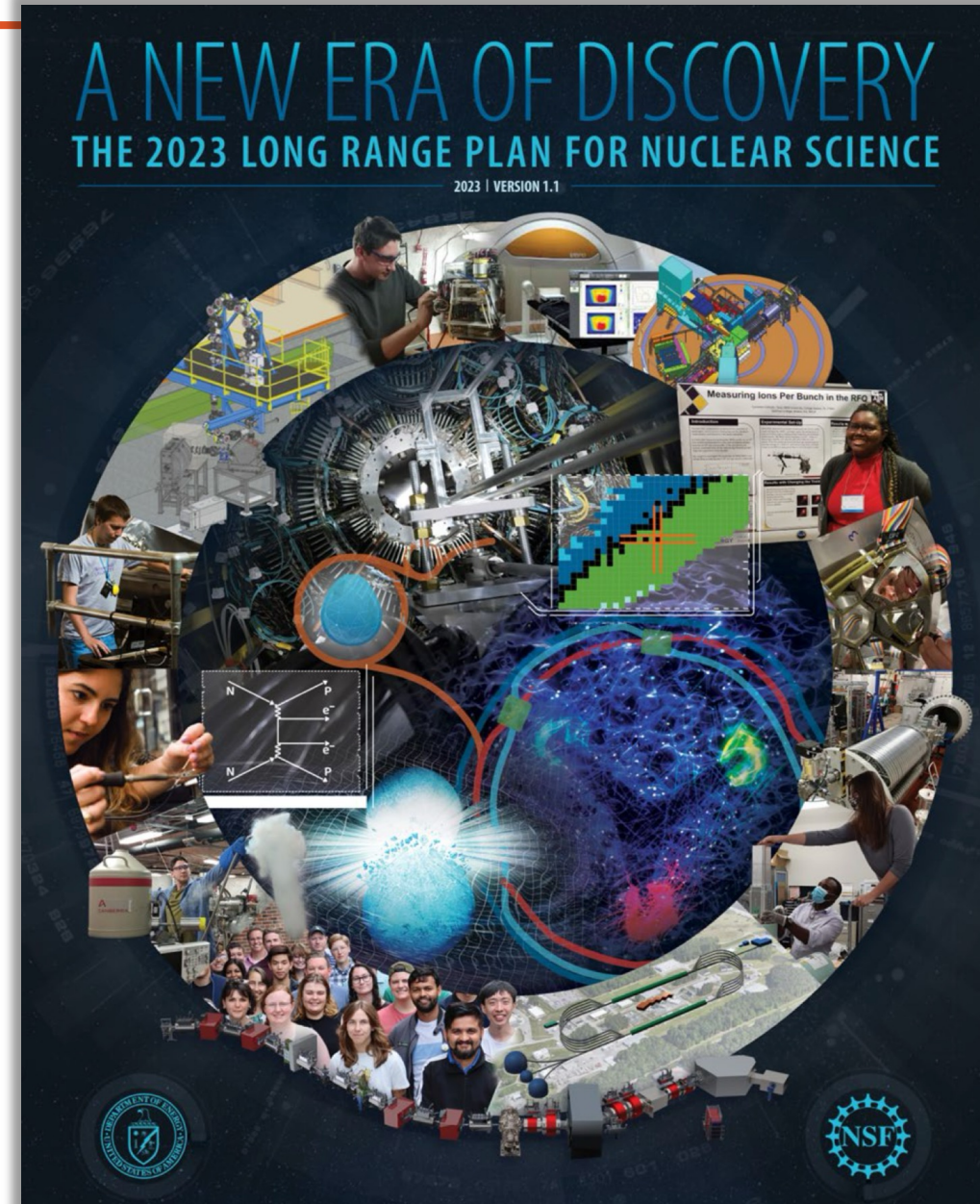
Nuclear mass spectra with LQCDMaster finished within 10 minutes.

Summary and Outlook

Polarized PDFs reveal how quark spins align with the nucleon spin, and TMDs promote this one-dimensional picture to a three-dimensional momentum image, exposing fundamental spin-momentum correlations.

Lattice QCD + LaMET is establishing a first-principles pathway from Euclidean correlation functions to physical partonic observables.

Together with global analyses and future EIC measurements, precision lattice calculations will open a new era of multidimensional nucleon imaging.



Summary and Outlook

探索AI Agent解决新特定科学问题的方案：eg. 双智能体强化学习拓展设计空间；

领域专精AI自主科学家：LQCDMaster 超长程高效探索+稳健数值计算+可信知识库

我们希望，*PhysMaster / LQCDMaster*可以

- ✓ 将智慧、思维活跃的物理学家从繁重的重复劳动中解放出来
- ✓ 加速灵感的生成与验证
- ✓ 解决之前解决不了的问题，拓展科研的边界

Thanks for your attention